AFRL-VS-HA-TR-2005-1013

Mission Support for the Communications/Navigation Outage Forecast System

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21 September 2005

Scientific Report No. 2

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This technical report has been reviewed and is approved for publication.

AFRL-VS-HA-TR-2005-1013

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
21-09-2005	Scientific Report No. 2	Sep 2004 - Sep 2005

4. TITLE AND SUBTITLE
Mission Support for the Communications/Navigation Outage Forecast System

5a. CONTRACT NUMBER F19628-03-C-0067
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 69120C

6. AUTHOR(S)
D. L. Hysell

5d. PROJECT NUMBER 1010
5e. TASK NUMBER CN
5f. WORK UNIT NUMBER A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cornell University
Dept. of Earth and Atmospheric Sciences
2108 Snee Hall
Ithaca, NY 14853

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010

10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/VSBXP

11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-VS-HA-TR-2005-1013

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This is a project to provide mission support for the Communication/Navigation Outage Forecast System (C/NOFS) through ground-based radar observations of background ionospheric parameters and of equatorial spread F (ESF) events from the Jicamarca Radio Observatory near Lima, Peru. A new theory regarding ionospheric preconditioning and the role of shear flow in destabilizing the postsunset equatorial ionosphere has emerged from C/NOFS pre-launch preparations at Jicamarca. An approximate, closed-form expression for the growth rate highlighting its dependence on background ionospheric parameters has been derived. The instability is expected to operate in regions of strong retrograde plasma motion where the background vertical density gradient is steep. Evidence that the instability occurs prior to the onset of conventional interchange instabilities comes from the periodic structure of precursor bottom-type scattering layers seen in radar imaging data.

15. SUBJECT TERMS
Keywords: space weather, ionospheric irregularities, scintillations, equatorial spread F, C/NOFS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	17	1Lt. K. Gruenstein
					19b. TELEPHONE NUMBER (include area code) 781 377-3107

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1. INTRODUCTION

This is a project to provide mission support for the Communication/Navigation Outage Forecast System (C/NOFS) under BAA VS-03-01 during its first four years of operation. Cornell will support the mission with ground-based radar observations of background ionospheric parameters and of equatorial spread F (ESF) events from the Jicamarca Radio Observatory near Lima, Peru. Jicamarca is capable of measuring ionospheric electric field and conductivity profiles from the valley region well into the topside ionosphere. Jicamarca can also make very detailed observations of ionospheric irregularities associated with ESF. Three main tasks will be supported under this project: (1) in-flight calibration of the electric field/drift meter sensors on board the spacecraft, (2) provision of Jicamarca radar support for experimental campaigns, both before the launch and during the satellite operations, and (3) analysis and interpretation of the data obtained during these campaigns in light of the C/NOFS mission goals.

2. METHODS AND PROCEDURES

The C/NOFS data workshop, co-chaired by Hysell, took place in January, 2005, in Estes Park, Colorado. At the meeting, a new theory regarding ionospheric preconditioning and the role of shear flow in destabilizing the postsunset equatorial ionosphere was presented. The theory, established in part using data from C/NOFS pre-launch preparations at Jicamarca, has important implications for forecasting ESF and for the conduct of the C/NOFS mission and is described in two publications supported by this award:

Hysell, D. L., and E. Kudeki, Collisional Shear instability in the equatorial F region ionosphere, *J. Geophys. Res.*, *109*, 10.1029//2004JA0106362004, 2004.

Hysell, D. L., E. Kudeki, and J. L. Chau, Possible preconditioning of the equatorial ionosphere by shear flow leading to spread F, *Annales Geophysicae*, in press, 2005.

The theory is summarized below.

Fig. 1 shows examples of ionospheric structure and circulation from paired events observed at Jicamarca in November or December 2001, 2002, and 2003. The top panel shown for each event represents relative backscatter power in grayscale logarithmic format. Regions of intense backscatter signify coherent scatter from plasma irregularities and are plotted using different amplitude scaling. The middle panel of each event in Fig. 1 shows vertical velocity derived from the average Doppler shift of Jicamarca's dual beams, which are directed approximately 3 degrees east and west of magnetic zenith for this experiment. The bottom panel shows zonal velocity derived from the difference of the dual beam Doppler shifts. The three examples on the left side of Fig. 1 represent events when ionospheric irregularities were confined to narrow layers in the bottomside. In contrast, the three examples on the right portray occurrences of "full-blown" equatorial spread F. Forecasting topside spread F events like these on the basis of available data is a goal of the C/NOFS mission. Forecast strategies have often involved applying a threshold condition to the intensity of the prereversal enhancement of the vertical drift. Cursory examination of the data here alone suggest that such a strategy should have merit but would be fallible and could not be applied before about 2330 UT (1830 LT) or only about an hour before the onset of instability.

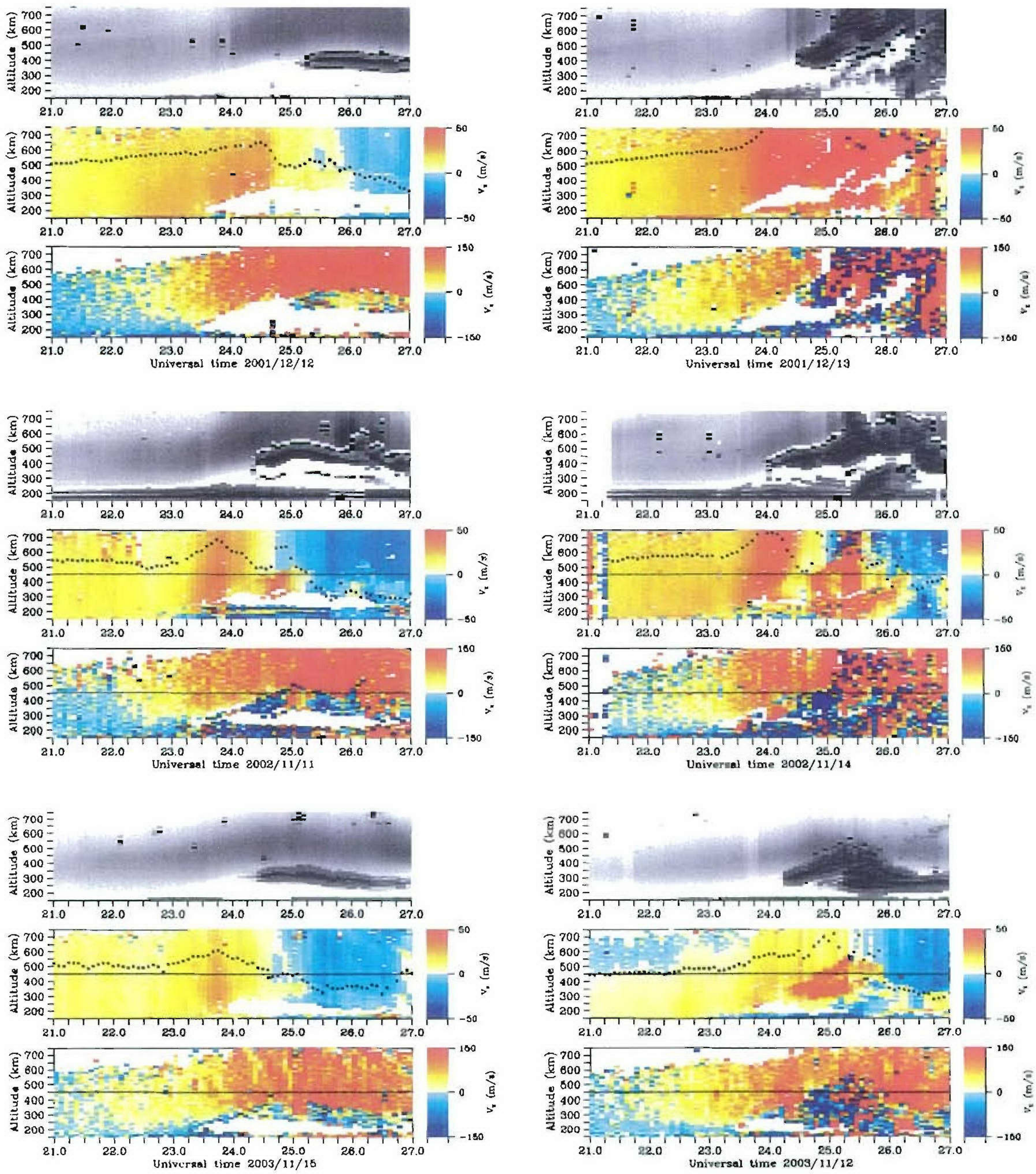

Figure 1: Six examples of ionospheric conditions around twilight. Each example shows the backscatter power (top panel), vertical plasma drift (middle panel), and zonal plasma drift (lower panel), plotted against the scales shown. Symbols plotted in the middle panel represent the vertical drift velocity at 450 km altitude for reference. The left and right columns portray events when topside spread F did not and did occur, respectively. Note that UT = LT + 5h.

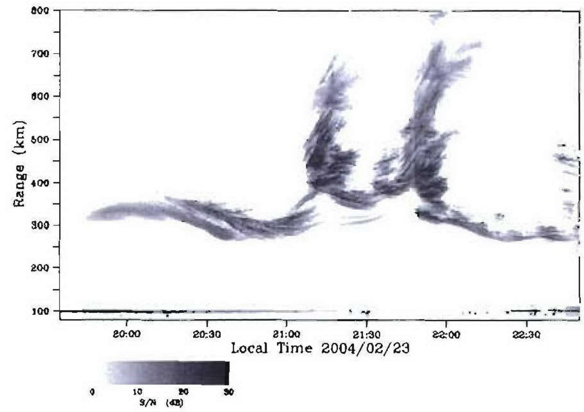

Figure 2: Range time intensity (RTI) image of a topside spread F event. Only a bottom-type layer was present prior to about 2100 LT.

Shear flow is evident in all of the events in Fig. 1 and is most obvious after about 0030 UT (1930 LT) when backscatter from bottom-type layers points to rapid westward motion immediately below regions of rapid eastward motion. It might seem fortuitous that the bottom-type layers exist to provide a radar target, since the valley region plasma is insufficiently dense to be monitored using incoherent scatter. However, [4] pointed out that, assuming the thermospheric winds are eastward throughout the F region, the bottom-type layers occupy strata where the plasma drifts are strongly retrograde. Given that significant horizontal density gradients are also present in these strata around sunset due to photochemical and dynamical effects, the strata would be prone to horizontal wind-driven interchange instabilities. They hypothesized that such instabilities are responsible for the bottom-type scattering layers.

Evidence that wind-driven instability is at work in the bottomside was provided by [1], who used aperture synthesis imaging techniques to analyze the structure of the primary waves in bottom-type scattering layers. The primary waves they observed appeared to grow by advection rather than convection, consistent with the wind driven interchange instability theory. Moreover, [1] found that the primary plasma waves in bottom-type layers sometimes cluster together in regular, wavelike patches. Clustering took place only in those events when topside spread F occurred later. They associated the clustering with a horizontal wave in the background plasma density that would present alternately stable and unstable horizontal gradients for wind-driven interchange instability. Fig. 3 shows a radar image derived from the bottom-type layer in Fig. 2 illustrating such clustering. Finally, [1] concluded that the clustered or patchy bottom-type layers were telltale of decakilometric waves in the bottomside F region that could serve to precondition or seed the ionosphere for gravitational interchange instabilities (Rayleigh Taylor) to follow. This hypothesis was supported by the fact that the intermediate-scale plasma irregularities that formed later in the spread F events shared the same decakilometric wavelength. This suggests a forecast strategy for spread F based on detecting clustering in bottom-type layers immediately after sunset.

Note that the 30 km wavelength of the clustering is roughly comparable to the vertical scale length of the plasma shear flow. Recently, [2] examined the possibility that shear flow itself may cause the bottomside F region to become unstable and produce the precursor waves inferred from radar imaging. If so, then shear flow could precondition the ionosphere for full-blown spread F.

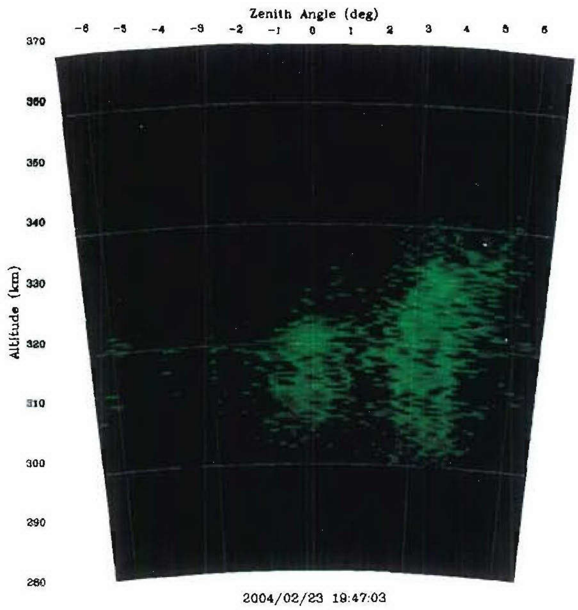

Figure 3: Radar image of plasma irregularities within the bottom-type layer seen in the previous figure. The irregularities are shown at the moment they first drifted westward into the radar illuminated volume.

[2] addressed the stability of the F region ionosphere in a sheared flow with an eigenvalue analysis. Following [3], [2] neglected Hall and parallel currents but allowed for polarization currents in their two-dimensional analysis:

$$\mathbf{J} = \frac{ne}{\Omega_i B}\left[\nu_{\text{in}}\left(\mathbf{E}+\mathbf{u}\times\mathbf{B}\right)+\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{E}\right] \tag{1}$$

The quasineutrality condition, together with the ion continuity equation, formed the basis of their model. Linearization of the model was performed according to

$$n(x,z) = n_\circ(z)+n_1(z)e^{i(k_x x-\omega t)} \tag{2}$$

$$\phi(x,z) = \phi_\circ(z)+\phi_1(z)e^{i(k_x x-\omega t)} \tag{3}$$

where terms with subscripts 0 and 1 represent zero- and first-order quantities, respectively, and where the Cartesian coordinates x, y, and z represented the eastward, northward, and upward directions at the magnetic equator. The linearized model equations took the form:

$$(\omega - k_x v_\circ)n_1 = -\frac{k_x}{B}\frac{dn_\circ}{dz}\phi_1 \tag{4}$$

$$\begin{aligned}&(\omega+i\nu_{\text{in}}-k_x v_\circ)\left[\frac{d}{dz}\left(n_\circ\frac{d\phi_1}{dz}\right)-n_\circ k_x^2\phi_1\right]\\ &= -in_\circ\frac{d\nu_{\text{in}}}{dz}\frac{d\phi_1}{dz}-k_x\frac{d}{dz}\left(n_\circ\frac{dv_\circ}{dz}\right)\phi_1\\ &\quad +i\frac{d}{dz}\left(B\nu_{\text{in}}(u-v_\circ)n_1\right)\end{aligned} \tag{5}$$

where ω is the complex frequency and serves as the eigenvalue, k_x is the assumed horizontal wavenumber, v_o is the background horizontal plasma flow speed arising from gradients in the zero-order electrostatic potential, and ν_{in} is the ion-neutral collision frequency.

This model was solved computationally for equilibrium velocity, collision frequency, and density profiles specified by:

$$\begin{aligned} v_o(z) &= V_o \mathrm{Tanh}(z/L) \\ \nu_{in}(z) &= \nu_o - \nu_1 \mathrm{Tanh}(z/L) \\ n_o(z) &= N_o u \frac{\nu_o/\nu_{in}(z)}{u - v_o(z)} \end{aligned}$$

and shown to yield rapidly growing solutions even in the collisional regime ($\nu_{in} \gg |\omega|$).

An approximate, closed-form expression for the growth rate highlighting its dependence on background ionospheric parameters is derived below. In our analysis, we focus on the collisional branch of the instability thought to operate in the bottomside equatorial F region by applying the limit $\nu_{in} \to \infty$ in (4) and (5), leading to:

$$\begin{aligned} &\frac{d}{dz}\left(\nu_{in} n_o \frac{d\phi_1}{dz}\right) - \nu_{in} n_o k_x^2 \phi_1 \\ &= -k_x \frac{d}{dz}\left(\nu_{in} \frac{u - v_o}{\omega - k_x v_o} \frac{dn_o}{dz} \phi_1\right) \end{aligned}$$

We next multiply the equation by ϕ_1^* and integrate over altitudes where the perturbed potential exists:

$$\begin{aligned} &-\int dz\, \nu_{in} n_o \left(|\phi_1'|^2 + k_x^2 |\phi_1|^2\right) \\ &= k_x \int dz\, \nu_{in} \frac{u - v_o}{\omega - k_x v_o} n_o{}' \phi_1 \phi_1^{*\prime} \end{aligned} \tag{6}$$

where the prime notation refers to differentiation with respect to z and where integration by parts has been employed. Since the left side of (6) is real, the frequency $\omega = \omega_r + i\gamma$ can only be complex valued if the eigenfunction ϕ_1 is also somewhere complex.

The numerical calculations of [2] suggested that in the vicinity of the shear node, where v_o'' vanishes and about which ϕ is localized, the complex potential can be approximated by $\phi(z) \approx \phi_o \exp(ik_z z)$. Utilizing this approximation and neglecting $\omega_r - k_x v_o$ by comparison to γ in this region, an expression for the growth rate γ can be derived from the real part of (6):

$$\begin{aligned} \gamma &\approx \frac{k_x k_z \int dz\, \nu_{in}(u - v_o) n_o{}' |\phi_1|^2}{k^2 \int dz\, \nu_{in} n_o |\phi_1|^2} \\ &= \frac{k_x k_z \langle \nu_{in}(u - v_o) n_o{}' \rangle}{k^2 \langle \nu_{in} n_o \rangle} \end{aligned} \tag{7}$$

where the averaging is weighted by the norm of the potential, a function that generally peaks about one scale height below the shear node and extends for several scale heights above and below it.

Given mode shapes and values for k_z derived from a complete boundary value analysis, (7) gives growth rate estimates in good agreement with the eigenvalues of the full model expressed by (4) and (5). The final expression shows that shear instability is likely to occur in layers with rapid retrograde plasma motion collocated with a steep vertical plasma density gradient. This is a testable hypothesis.

The task remaining is to test and validate the shear instability model using existing ground based data and, when available, in situ observations from C/NOFS. We can then assess the importance of shear flow in determining the stability of the postsunset ionosphere. The capabilities of the Jicamarca radar, along with samples of our data products and their relevance to this model, were presented to the spring C/NOFS science team at Hanscom and the June CEDAR meeting in Santa Fe, where Jicamarca scheduling, calibration and validation issues, and larger issues pertaining to ionospheric stability and scintillation forecasts were also discussed. We are presently upgrading the radar mode with which we will support the satellite after launch and planning our modeling strategy.

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